EXPERIMENTS WITH EXPLOSIVELY FORMED FUSE OPENING SWITCHES IN HIGHER EFFICIENCY CIRCUITS*

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Abstract

We have previously reported on the development of explosively formed fuse (EFF) opening switches for use in applications where very long conduction times (10's or 100's μs) are required and where opening times of 1–10 μs are adequate. In this paper we report on the development of an EFF that allows magnetic flux in the switch to be delivered to the load rather than lost from the circuit. The topology of this device is substantially different from earlier versions and contains new design constraints. In the most strenuous test to date, we delivered 7.5 MA to the EFF from a small helical explosive driven magnetic flux compression generator, and completely turned off the current in the remaining 34-nH circuit in ~3 μs producing a 140-kV pulse. The switch in this test is 15 cm in length. We also report on work with EFFs in this configuration tailored for slightly longer opening times.

Introduction

Explosively formed fuse (EFF) opening switches have been the subject of a variety of publications[1–4] as the concept and technique have evolved. These devices are particularly useful for pulse shaping in explosive driven magnetic flux compression generator (explosive generator) applications in which multi-megampere currents need to be diverted to low-inductance loads or interrupted to produce large voltages across high-impedance loads. The time scales for these applications are typically one to a few microseconds. In previous reports we have noted that a switch topology could be pursued for EFFs that would be more efficient than that used in early development work.[4] We have now performed EFF tests in this configuration and the results are the subject of this paper.

Explosively formed fuses are opening switches actuated by explosively extruding conducting sheets (typically Al) into a series of thin sections that become resistive due to extrusion and Joule heating effects. Most EFFs for practical use are cylindrical devices and the resistance of the switch is a function of ℓ/C where ℓ is the length of the switch and C its circumference. In addition, the energy an EFF will dissipate varies as ℓC. These relationships are more carefully described in Ref. 3.

Figures 1 and 2 describe two topologically different EFF circuits that we will refer to as Type 1 and Type 2, respectively. Our Type-1 device is the one with which most of our experience is accrued, but which wastes flux during the current diversion process. Although in some applications this is not significant, other important cases are very inefficient in this mode. The Type-2 device is the subject of this paper. Although this device makes efficient use of the stored magnetic flux, there are additional engineering concerns that arise in this design that we have not addressed until now. Figure 3 shows a cutaway of a practical small-scale Type-2 switch. Magnetic flux is compressed into the inductive store of the device with a small helical explosive generator. The shock wave from an axially initiated cylindrical HE charge initiates a second high explosive (HE) cylinder that extrudes the switch conductor into the extrusion die. The output of the device is derived from the inner and outer conducting layers.

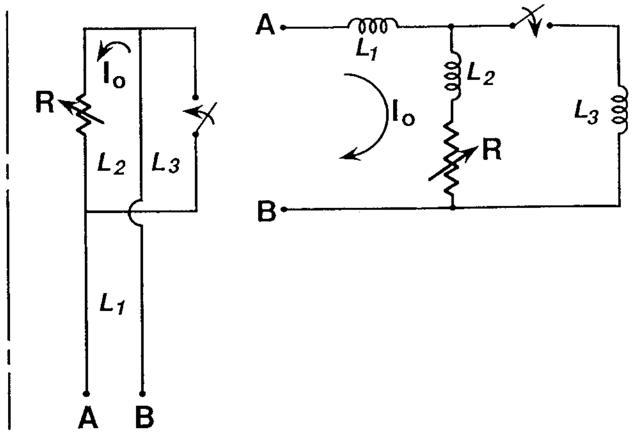

Fig. 1. Pictorial representation and schematic of a Type-1 EFF. The center line in the illustration indicates that the device is a figure of revolution of the lines shown. L_1, L_2, and L_3 relate the inductance in the schematic to a volume in the device, and R is the active opening switch element. A and B are the connection points to an explosive generator. Flux in L_1 is available to be transferred to the load, L_3, when the closing switch closes, but all flux ($L_2 I_o$) in the opening switch loop is lost.

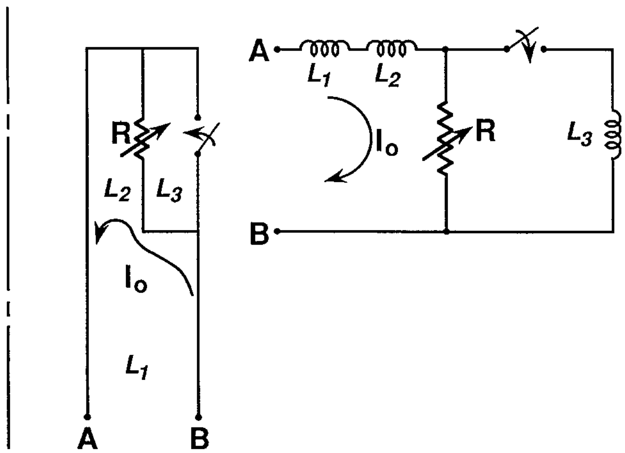

Fig. 2. The same two representations for a Type-2 EFF as presented for a Type-1 EFF in Fig. 1. L_1 and L_2 are kept separate to illustrate the point that some inductance is still associated with the EFF device, but L_1 and L_2 can be lumped together ($L_1 + L_2 = L_{\mathrm{STORE}}$) for circuit analysis.

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14. ABSTRACT

We have previously reported on the development of explosively formed fuse (EFF) opening switches for use in applications where very long conduction times (lO's or lOG's p.s) are required and where opening times of 1-10 p.s are adequate. In this paper we report on the development of an EFF that allows magnetic flux in the switch to be delivered to the load rather than lost from the circuit. The topology of this device is substantially different from earlier versions and contains new design constraints. In the most strenuous test to date, we delivered 7.5 MA to the EFF from a small helical explosive driven magnetic flux compression generator, and completely turned off the current in the remaining 34-nH circuit in ~3 p.s producing a 140-kV pulse. The switch in this test is 15 em in length. We also report on work with EFFs in this configuration tailored for slightly longer opening times.

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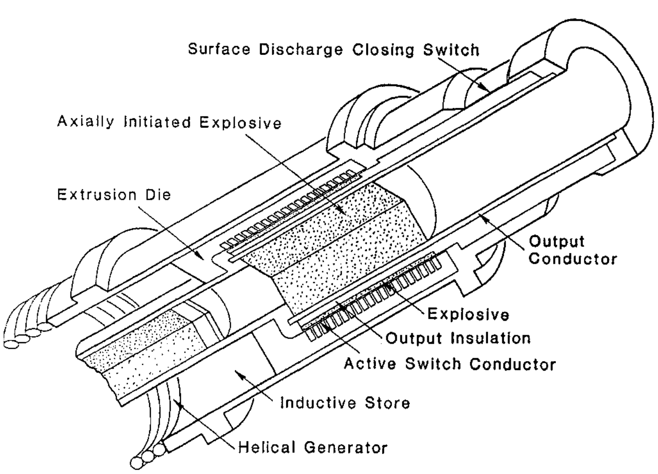

Fig. 3. Small-scale Type-2 EFF.

Engineering Considerations

A variety of new engineering concerns must be addressed to make use of Type-2 devices. As can be seen in Fig. 3, the switch consists of seven cylindrical layers. Starting with the axial detonation of an inner HE cylinder, a shock wave passes through an output conductor, output insulation, and redetonates a second layer of HE. The second layer of HE, once detonated, drives the active switch conductor into the extrusion die outside of which is the return current path. The first new concern with Type-2 switches is the detonation of the HE. In many applications, both ends of the coaxial system will be closed and detonator firing devices will have to pass through two conducting layers of the device that are at different electric potentials and enclose a large pulsed magnetic field. Our small-scale tests had one open end, as shown, and we have not experimentally addressed this difficulty to date. However, we are developing detonator firing units that can be housed in the flux-free region inside the generator armature, and require only fiber-optic control leads which can be run through low-voltage regions where insulators bridge the gap anyway. The second concern to address is that the output current must flow through a conductor that has experienced an extremely high-pressure shock wave. Conductors do not heat appreciably under these conditions and tend toward higher conductivity as they are compressed. As a result, the only substantial issue is not shearing the conductor before the pulse is delivered. We will show in later figures that this has not been a serious problem. Finally, the major concern is for the integrity of the highly shocked output insulation. Teflon has proved to remain a good insulator at pressures of a few tens of GPa, and hence, shearing the insulation at some edge is again the largest concern. While we can calculate the hydrodynamic reaction of our devices in good detail, we felt that the issue of voltage standoff at the output conductor had to be experimentally verified.

2-D Hydrodynamic Calculations

From experience with Type-1 devices we have gained considerable confidence in our ability to describe qualitatively the opening switch action of an EFF by examining 2-D hydrodynamic code (hydro-code) calculations. In addition, two of the three new engineering concerns previously raised are hydrodynamic issues. As a result, our first step in developing Type-2 EFFs was to perform 2-D hydro-code calculations of our specific geometries. In addition to the device depicted in Fig. 3, we also had an immediate interest in a slower opening EFF. Figures 4 and 5 are calculations of the performance of a fast Type-2 EFF as shown in Fig. 3, and of a device that opens

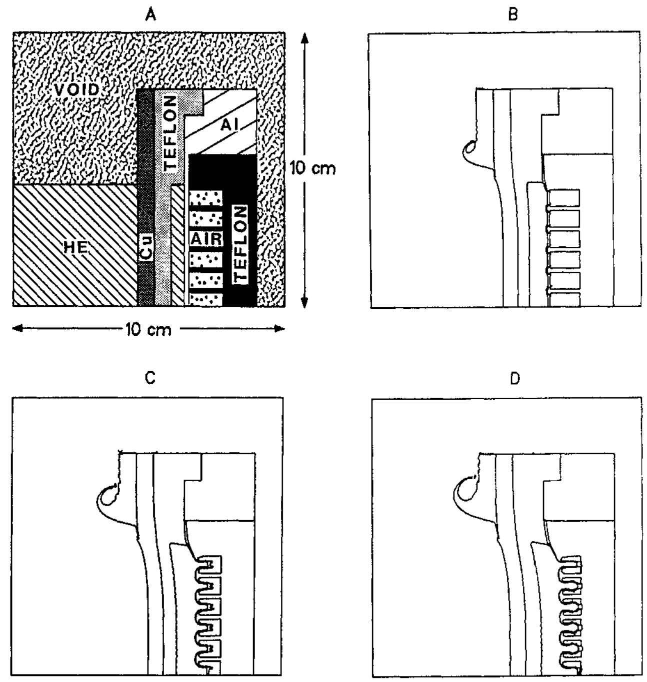

Fig. 4. Hydro-code calculation of the response of a segment including the output end of a fast Type-2 EFF. Frame A shows the device configuration before the HE is detonated, and identifies the various switch materials. The left side of each frame is the cylindrical axis. Frames B, C, and D show the evolution at 9, 11, and 12 μs after the axial detonation occurs. The second charge, shown cross hatched the same as the inner HE charge, is detonated by a shock wave from the first, but calculations indicate a run to detonation in the second charge of ~2.5 mm. Note that neither the output conductor nor insulation are sheared.

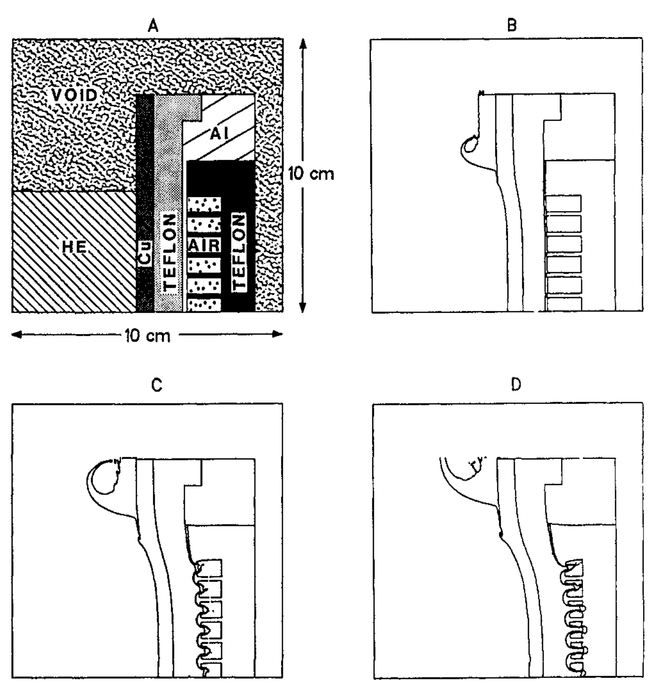

Fig. 5. Hydro-code calculation of the response of a slowed down Type-2 EFF. The second explosive layer is omitted from this version, and the volume is filled with Teflon. Frames A, B, C, and D represent time = 0, 10, 14, and 17 μs respectively relative to axial detonation time.

more slowly by virtue of leaving out the second layer of HE. In this version, the active switch conductor is extruded by the motion of the Teflon insulator. Note in both of the figures that neither the output conductor nor the output insulator are sheared when the components are arranged as drawn. The hydrodynamic response seen in these calculations seemed sufficient to provide the desired switching, and it is with these two devices that we conducted opening switch tests.

Experimental Results

We have conducted three tests of our small-scale Type-2 EFFs. Each of these had a different purpose and we will describe the significant parts of each. Two of our tests were with the fast opening switch version shown in Fig. 3, and the other with the slowed version. The first of our fast-switch tests was conducted with the goal of ascertaining whether an EFF thus designed would function as an opening switch and what the approximate circuit-opening parameters would be. Magnetic energy for these tests was supplied by a small helical explosive generator and Fig. 6 summarizes the results. 3.8 MA were generated with the profile shown, and the EFF opened, dissipating all the circuit energy in the inductive store (190 kJ). The derived storage inductance is 20 nH. The indicated EFF resistance was generated and produced a 70-kV voltage spike as shown. This test proved the concept and the most significant remaining question was how much voltage the shocked output insulator could withstand. One particular application of interest requires a ~130-kV holdoff. By attaching a 52-nH coaxial section to our generator and increasing the current risetime accordingly, we approximately doubled the peak current in our second test, with the goal of producing a large enough voltage pulse to cause output insulator failure. At this level we were operating above the approximate energy limit of 750 kJ determined by Type-1 tests for a switch this size. The results of the test are summarized in Fig. 7. At a current of 8 MA, the voltage spike generated was 142 kV and no failure of the Teflon insulation occurred. At switch time, 34 nH remained in the circuit and the entire 1.1-MJ circuit energy was dissipated. Although all the circuit energy was dissipated, we see that the resistance begins to decay near the end of the test.

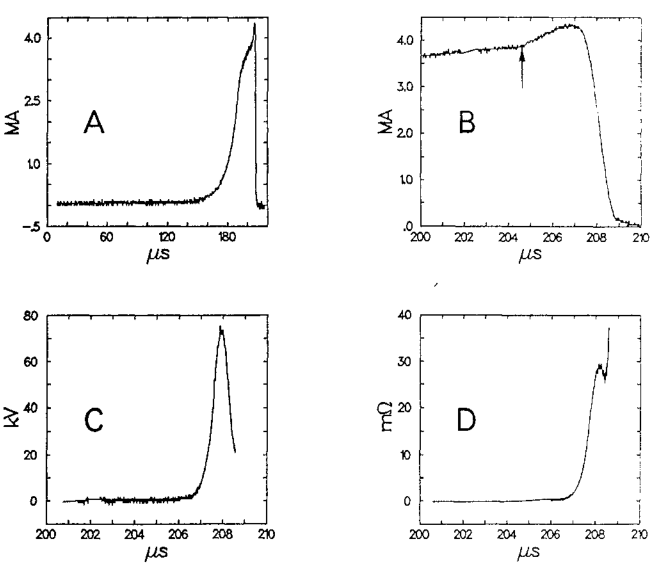

Fig. 6. Results from initial Type-2 EFF test. Frames A, B, C, and D are the total current pulse, the current pulse at switch time, the voltage measured and the resistance obtained, respectively. Note that the generator supplies 3.8 MA and flux compression in the switch increases the current to 4.3 MA. The resistance profile is cut off at the level shown, but analysis shows it going to a high value. This part of the signal is due to dividing two small signals and is not very accurate. The arrow in (B) shows the time of Frame B in Fig. 4.

Our first application for Type-2 EFFs will be to drive a plasma flow switch that has a few μs run time. To drive this properly, a slower switch than that indicated by the previous data is required. Since we had previously shown that a switch could be made with Teflon rather than HE in contact with the active conductor, we ran a calculation in which the only change from the device in Fig. 3 was that Teflon replaced the second explosive layer. This calculation is shown in Fig. 5. Since this appeared to have the approximate time scale of interest, we proceeded with a test. The results are shown in Fig. 8. The voltage and resistance profiles are now spread out over ~8 μs, and yet the entire circuit energy is still dissipated. The losses due to the free surfaces at the HE ends are substantial in this 15-cm-long version, and the R(t) curve for such a switch that is longer should be proportional to the resistance developed in the lossless section. We predict a relatively higher resistance per length on scaled-up devices.

EFF Analysis

To date, we have not been able to quantify the amount of resistance increase in an EFF that is due to extrusion heating and the amount due to Joule heating. With two identical assemblies that dissipated a factor of five different energies, we felt it would be possible to address this issue. Close comparison of the two resistance curves in Figs. 6 and 7 shows that the resistance profiles are more similar early in the experiment than we would have expected from intuition, given the large difference in dissipated energy and power. This suggests that extrusion effects may be more important than we previously thought. On the other hand, the low-energy experiment shows an abrupt resistance increase at the end (cut off in the figure) where the high-energy test does not. We have previously attributed this to fuse-like phenomena. To examine the question further we compared results from our hydro-code and a code intended for calculations of electrically exploded foil fuses.[5,6] From the hydro-code calculations we extract that geometric changes give rise to a factor of 25–50 resistance increase for the extrusion die shown. This would cause our switch in these tests (15-cm long and 40 cm in circumference with 0.08-cm-thick Al initially) to increase from 14 $\mu\Omega$ to 350–700 $\mu\Omega$. An increase of another factor of 75–150 is still required to achieve the resistances achieved by peak voltage in the tests. To get a measure of how much electrical heating might be achieved, we estimated a length and cross section for the active volume of the EFF from a hydro-code calculation time between when the experimentally measured resistance becomes significant and the time of peak voltage. This corresponds roughly to Frame C in Fig. 4, although the estimate came from a more finely zoned calculation than that shown. This cross section was then input to our fuse code and run as a fuse calculation for the storage inductances and currents in the tests. In addition, to simulate extrusion heating effects, we ran the problem with a range of initial material temperatures corresponding to initial states from ambient temperature up to 2.5 eV. Results were strikingly similar to those of the experiments and provided some surprises. The main surprise is that the results were not strongly affected by the extra initial energy in the active volume. All calculations showed electrical fusing to occur on appropriate time scales, although the highest initial temperatures were clearly beginning to reconduct earlier than even in the high-energy experiment. The set of calculations that best reproduced experimental results were those that added 0.1 eV (~1000 K) initially, although the agreement between a few

calculations in the set were well within the errors due to the many approximations made. The remaining question is to examine both the similarities and differences in the two resistance profiles. Our fuse code incorporates hydrodynamic effects for fuses within the context of the deposited internal energy and inertial tamping. The resistance a fuse achieves is determined by its trajectory in density-temperature (ρT) space, and resistance increase (R/R_o) contours are complicated curves on

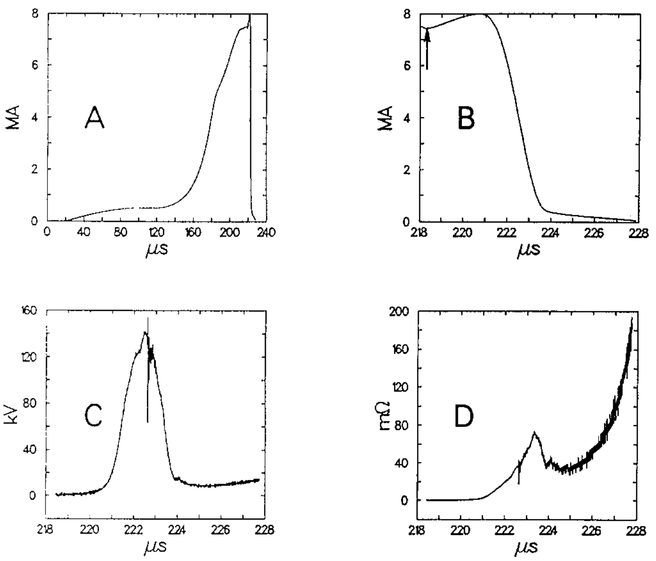

Fig. 7. Results from Type-2 EFF test at higher current. The frames show the same profiles as Fig. 6. Note that the generator supplied 7.5 MA to the device, and flux compression in the switch boosted the current to 8 MA. In Frame C, we see that a peak voltage of 142 kV was developed across the 15-cm switch. Because of the nature of dividing the small signal in (C) by the small signal in (B), the resistance increase seen after ~225 μs should be taken as uncertain. The arrow in (B) shows the time of Frame B in Fig. 4.

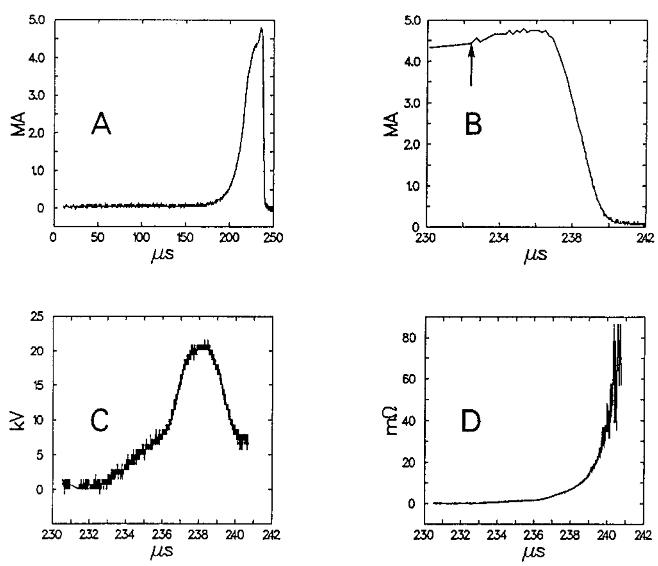

Fig. 8. Performance curves from a slowed Type-2 device. The lower resistance and rate-of-resistance increase will drive a slower load pulse. The arrow in (B) shows the time of Frame B in Fig. 5.

that plane.[5,6] In plotting the ρT trajectories for the calculations that best matched our results, the following insight was obtained. Both trajectories, though different, followed paths that crossed R/R_o contours at about the same rate early in the experiment. The trajectory for the low-energy test, however, remained in a region of the plane where the R/R_o contours are close together and small effects (such as cooling by expansion) toward the end of the experiment allowed it to cross the contours abruptly. The high-energy trajectory, however, went into a region of the plane where R/R_o contours are far apart and any major changes in resistance require a large stimulus. With this insight, we are able to explain the EFF behavior based just on fuse-like behavior.

Conclusions

In this work, we have shown that Type-2 EFFs will operate as predicted, and that our output insulator will withstand substantial voltage. In addition, we have shown that while there may be extrusion heating effects, they are unimportant compared to Joule heating. This has previously been an unproved assumption.

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